



Unavoidable solutions for coastal adaptation in Reunion Island (Indian Ocean)

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ABSTRACT

The study of recent past trajectories of vulnerability to climate-related hazards allows for highlighting the prevailing environmental and anthropogenic drivers that operated over the last fifty to sixty years and given latency phenomena in social systems, therefore have the potential to continue driving a system's vulnerability in the coming decades. Stop or even reverse these trends represents as much unavoidable solutions for enhancing concrete long-term adaptation to climate change, whatever the end-century warming scenario.

Using the case study of Reunion Island (Indian Ocean), we emphasize four major drivers of the recent coastal trajectory of vulnerability, i.e. changes in human-built assets, shoreline position, natural buffers' characteristics, and the extent of coastal protection structures. Together, these drivers highlight the need for controlling the urbanisation process to reduce the anthropogenic pressures exerted on morphological-ecological systems, restoring the buffering function of the latter, and moving towards a less hard structure-dependent coastal defence strategy. Such a shift in coastal management however supposes some radical changes in the way coastal development strategies consider environmental issues (hazards, resources and services). Here we bring empirical material showing that neither Reunion Island decision-makers are keen to drive such radical changes, nor the population is ready to accept potentially constraining policies that will have benefits only in the future. We conclude on the need for further advancing the design of adaptation pathways that build on the implementation of context-specific unavoidable solutions, and thus that seriously consider limiting the risk of maladaptation as a baseline strategy.

1. Introduction

The identification of climate change adaptation solutions that can be implemented now and allow bypassing the problem of uncertainty on future global warming and induced local impacts, is a growing concern worldwide. Prior to the 21st Conference of the Parties of the United Framework Convention on Climate Change (COP21) in 2015, the international community shifted from the design of the problem to the “era of solutions” (UNFCCC, 2014). Similarly, the scientific community gets more and more involved in practice-oriented analyses, notably with growing efforts into understanding the maladaptation and adaptation pathways issues. Maladaptation refers to adaptation-labelled initiatives that can actually turn out to be harmful, and so to the risk that efforts aiming at fostering adaptation in the short-term in fact affect territories', sectors', and people's long-term capacity and opportunities to cope with the impacts of climate change (Juhola et al., 2016; Magnan et al., 2016). A critical underlying question deals here with the

identification of tangible ways to prevent the risk of maladaptation. The adaptation pathways literature advocates that any long-term adaptation strategy of a particular decision-maker must be based upon decision cycles that sequence a set of possible actions based on alternative external, uncertain developments (Haasnoot et al., 2013; Barnett et al., 2014; Wise et al., 2014; Fazey et al., 2016). However, a critical underlying question refers to the identification of both the first solutions to be put in place and the sequencing of initiatives on the long run. A third contextual element pushes for advancing the “era of solutions” further. There is indeed a risk that the IPCC Special Report on the impacts of a + 1.5 °C world does not intentionally allow for the uncertainty problem to get back on stage. In the substance, this report questions the feasibility for the global society to effectively decarbonize its development patterns (Fawcett et al., 2015; Anderson and Peters, 2016), and for the scientific community to bring new evidence on the differential local-scale impacts induced by only few tenths of a degree in global temperature on a multi-decadal scale (Mitchell et al., 2016;

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Peters, 2016; Schleussner et al., 2016). These two aspects encompass considerable sources of uncertainty. Regarding impacts, scientists legitimately deliver results in terms of probability and ranges of uncertainty, such as illustrated in recent studies on long-term sea-level rise (Schaeffer et al., 2012), on the future of Mediterranean ecosystems (Guiot and Cramer, 2016) and on global marine fisheries (Cheung et al., 2016). While science is clear on the fact that uncertainty cannot prevent decision and action (Stafford-Smith et al., 2011; Hallegatte et al., 2016; Oppenheimer and Alley, 2016), there is still a risk that the decision-making arena uses uncertainty as an alibi to postpone difficult decisions (e.g., relocation of economic activities or settlements). This would however have exponential detrimental effects worldwide, and so there is a crucial need for science to reaffirm that taking now long-term adaptation-compatible action is possible.

In this aim, scientists suggest to explore the consequences of different choices under various end-century warming scenarios (Hallegatte et al., 2016), based for example on the assessment of the risks of impact of such contrasting futures on social-ecological systems (Gattuso et al., 2015; O'Neill et al., 2017). Here, we argue for a complementary way that aims at drawing lessons from the recent past rather than only looking forward to the long-term future, in order to demonstrate that critical solutions for the future already exist. This refers to the “Trajectory of Vulnerability” approach (ToV), which consists in designing part of the adaptation solutions based on the lessons learnt from storylines highlighting the prevailing drivers of a given coastal system’s vulnerability to climate variability and change over the last five to six decades (Duvat et al., 2017). Because of path-dependency effects inherent to both social systems inertia (e.g., Fehr-Duda, 2016) and lock-in phenomena (e.g. in urban processes; Reyna and Chester, 2014), and in the context of sea-level rise, the observed multi-decadal drivers have the potential to continue driving the system’s vulnerability in the coming decades (Duvat et al., 2017). Accordingly, actions to overcome past-to-present trends represent an area of “unavoidable” solutions and constitute together a first pragmatic step to both limit maladaptation and enhance long-term adaptation pathways.

Here, we use the case study of Reunion Island to demonstrate the relevance of studying the past-to-present drivers of vulnerability in order to highlight the unavoidable solutions for coastal adaptation. Looking backward however raises a major question for the Present, namely about the ability of a given society to effectively implement well-known solutions to well-known problems. Using empirical material on Reunion Island decision-makers’ visions of the future and on coastal residents’ perceptions of current to future climate-related coastal risks, we discuss how neither the formers are ready to drive radical change towards more climate-proof coastal development strategies, nor the latter are keen to accept potentially constraining policies that will mainly have delayed benefits. We also analyse and discuss the need for further advancing the design of adaptation pathways that build on the implementation of context-specific unavoidable solutions, and thus that seriously consider limiting the risk of maladaptation as a baseline strategy.

2. Study area

Reunion Island is a French overseas territory located in the south-western Indian Ocean (21°10'S, 55°30'E). It has a land area of 2512 km², with its highest point at 3070 m above sea level (Piton des Neiges inactive volcano). Its 240 km-long coastline is made of a variety of morphological features, including three main river deltas, high and low rocky coasts, as well as volcanic and coral beach-dune systems, most of which are bordered with fringing coral reefs (Cazes-Duvat and Paskoff, 2004). Its 850,727 inhabitants¹ are mostly located in the coastal zone. With an economy based on services, tourism and

agriculture, and a Gross National Income per capita higher than \$23,000, this case is representative of a High-income economy according to the World Bank Income Groups² (GNI > \$12,476 per capita), and its coastal development patterns follow the worldwide trend, i.e. densification and urbanisation (Wong et al., 2014).

The study area covers 39.7 km of coastline from north to south along the western side of the island, where most of the population and economic activities concentrate. It is composed of four municipalities that this paper uses as case studies, including the island’s two main urban centres (Saint-Denis in the north, 146,985 inhabitants; and Saint-Pierre in the south, 84,063 inhab.), its industrial harbour (Le Port, 35,280 inhab.) and its first municipality for coastal tourism (Saint-Paul, 105,967 inhab.). In addition to urbanised seafronts, the area exhibits alluvial features made of volcanic material, such as sand and pebble beaches bordered with sand dunes, coral coasts made of beach-dune systems fringed with embryonic to fringing coral reefs, and rocky volcanic coasts including low-lying areas and cliffs (Cazes-Duvat and Paskoff, 2004). The whole area is prone to tropical cyclones and distant-source swells, both of which frequently generating impacts on coastal morphology (i.e., erosion and accretion, and marine inundation), vegetation and human assets (Duvat et al., 2016a).

3. Material and methods

This study involves three datasets that have thus far only been published in French and analysed separately (Duvat and Salmon, 2015; Magnan et al., 2015; Duvat et al., 2016b; Magnan and Charpentier, 2016). The added-value of this paper relies in the combination of their main results into an integrative analysis going from the drivers of vulnerability to adaptation-related issues.

The first dataset refers to the characterization of the changes that have occurred between 1950 and 2011 in human-built assets (number and location of buildings and key infrastructures), shoreline position (calculation of shoreline change rates and analysis of human-driven disruption of natural processes), terrestrial natural buffer zones (extent, nature and buffering functions of beach-dune systems and alluvial features such as coastal deltas) and coastal protection structures (extent, nature, condition and dimensions). This dataset covers the four studied municipalities, i.e. Saint-Denis, Le Port, Saint-Paul and Saint-Pierre. For each of the above-mentioned items, data were generated based on multi-date aerial image analysis, i.e. on the comparison of historical aerial photographs provided by the Institut Géographique National (IGN) for 1950 and 1978, with the 2011 ortho-photography provided by the IGN. Each historic aerial photograph was georeferenced and integrated into a Geographic Information System (GIS) using ArcGIS 10.2 software. This allowed conducting a comparative analysis of the three data series (1950, 1978 and 2011), and emphasizing specific changes, for example in terms of (i) buildings’ distance to the shoreline (using the “near” tool of the ArcGIS software, which allows for calculating the minimal distance between two entities, here a building and the shoreline), (ii) terrestrial natural buffer zones contraction, or (iii) shoreline change (using the Digital Shoreline Analysis System software, DSAS). The buildings’ elevation values were extracted using Lidar elevation data (2012-issued Litto3D[®] IGN, data collected between September 2008 and October 2010, precision in elevation of 20 cm) applied to the centroid of each building. To document coastal protection structures (location, nature, condition and dimensions, see Duvat (2013) for details on the methodology) and their contribution to the disruption of natural processes (Duvat and Salmon, 2015), we used multi-date aerial image analysis and fieldwork, which was conducted between 2012 and 2016. Two limitations must be mentioned here that

² Data for 2015. Source: INSEE Reunion, <https://www.insee.fr/fr/statistiques?debut=0&idprec=3290942&theme=0&collection=32+113+86>.

¹ <https://www.insee.fr/fr/information/2018985>.

however do not dramatically affect the results. First, the lack of data on the nature of human assets (i.e. materials used for buildings and number of storeys) for past periods of time made a comprehensive comparison with today's situation impossible. To overcome this problem, we only considered each asset's distance to the shoreline and elevation. Regarding elevation, in the absence of high resolution elevation data prior to the 2012 Lidar and based on existing knowledge (i.e. archive documents and discussion with colleagues involved in coastal research on the island for decades), we considered that no major change in topography occurred in the studied areas between 1950 and today. Therefore, we used the 2012-issued Lidar data for all time periods. Despite this necessarily introduces a bias (which we considered to be acceptable), this allowed highlighting major changes in human asset exposure. A second limitation deals with coastal protection structures, as no data exist on their past features, what made a comparative analysis between the Past and Present impossible. For the Past (1950 and 1978), we therefore generated data (location and extent of these structures) based on aerial image analysis. Although extracting protection structures from aerial images using photo-interpretation implies the omission of some structures (due either to their small size, or to their masking by the vegetation), this however allowed emphasizing the marked increase in the extent of protection structures and therefore in the proportion of protected shoreline.

The second dataset refers to Reunion Island stakeholders' visions of the future. In total, 29 qualitative interviews (~1 h each) were conducted between January and March 2015: 20 with policy actors operating on the island scale, among which 13 concerned the municipality level and 7 the supra-municipal level (State, regional institutions and public bodies); and 9 with economic actors (diving centres managers, restaurants owners, resorts directors and fishermen). The interviews were designed to understand stakeholders' view about Reunion Island coastal area's current environmental and anthropogenic features; their perceptions of the possible changes in the near (~2025) and long term (~2050); and the possible responses to be promoted. The semi-structured interview guide addressed the four above-mentioned items (shoreline change, natural terrestrial buffer zones extent, assets exposure to climate-related coastal hazards, and coastal defence), as well as two additional ones relating to risk management policies (strengths and weaknesses in implementation) and climate change (perception of the induced threats and related timing). Using graphics showing the results of the first phase of the research, i.e. 1950-today ToVs, participants were asked to give their view on future trends (~2025 and ~2050 time horizons), at both the island and the municipality levels, regarding coastal erosion, assets exposure, natural terrestrial buffer zones and coastal defence. Only the order of magnitude of future changes were requested (using scientifically-based pre-defined figures and scales), the aim being first to capture the perceived trends, and second to see whether the interviewees envisage major differences between ~2025 and ~2050 timescales. Participants were then asked to freely identify the driving factors explaining their perceived trends, e.g. population growth and related demand for new buildings, economic trends, transportation facilities development, urbanisation regulation, increase in climate stressors such as tropical cyclones or changes in sea level, etc. The aim was to determine the respective weights of anthropogenic and natural drivers of change in the stakeholders' perceptions of the future. Last, participants were asked to suggest which responses should be promoted to address the challenges they identified and reduce long-term vulnerability to coastal hazards (including both extreme events and gradual changes). The guide, which was composed of about fifty questions, lastly included information on the interviewee (age, scope of his/her responsibilities, experience in his/her function, experience in the occurrence of coastal hazards, etc.).

The third dataset deals with Reunion Island coastal residents' perceptions of contemporary and future climate-related coastal risks. The sample consisted of 479 coastal residents, 85% being between 20 and 60 years old and 8% > 60 years old. Around 69% and 31% of

interviewees were living < 500 m and < 100 m from the shoreline, respectively, with > 60% having already experienced at least one powerful sea-related event (either a tropical cyclone or distant-source swells) in their life. The interviews lasted ~30 min each, and were conducted between November 2013 and March 2014 by face-to-face discussions (263 interviews) and by phone (216). The questionnaire was composed of 57 questions: 12 on the interviewee's personal information (age, job, property status and leisure activities related to the sea); 8 on his/her general knowledge on coastal hazards (tropical cyclones, distant-source swells; period of occurrence, associated processes and impacts); 9 on his/her own experience of previous events (date or name of the event/s, actions undertaken before/during/after the event/s, impacts suffered); 13 on his/her views on coastal defence and risk management (benefits and limitations of protection structures and related responsibilities for implementation and maintenance, knowledge on existing risk management policies); 2 on his/her sense of safety regarding living at the coast (including a question on the possible desire to move away); and 13 on his/her perception of the risks induced by climate change (trends in the frequency and intensity of extreme events, increase in impacts on human assets and the coastal environment, and means to face these threats). Regarding climate change, participants were asked to consider three time horizons going from the near (~2025) to the distant (~2050) and very distant (~2080) future, in the aim of capturing their capacity to look to the long-term future, and to identify the time slot that would signal to them a key turning point in environmental conditions. In addition to the 479-people survey, 37 more in-depth interviews were conducted with coastal residents over 20 years old and living in the four studied municipalities. These more qualitative interviews allowed going further in terms of people's understanding of the benefits and limitations of hard protection structures, the contribution of anthropogenic/natural drivers to coastal erosion and buffer zones contraction, or the types of stakeholders supposed to be in charge of preventing future risks.

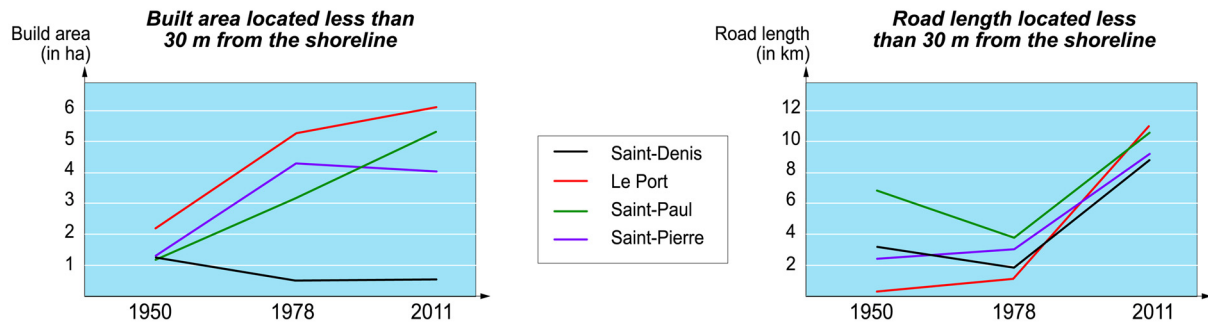
4. Synthesis on the drivers of recent past trajectories of vulnerability

The recognition of Reunion Island as a French department in 1946 allowed for the progressive improvement of living and health conditions as well as the development of a modern economy. This resulted in a threefold increase in population from 1950 to 2014 that triggered the emergence at Le Port and Saint-Paul municipalities, and the increase at Saint-Pierre and Saint-Denis municipalities, of exposure and vulnerability to climate-related coastal hazards. Similar explaining processes can be highlighted across the four municipalities.

The changes measured in the study area (i.e. aggregation of the results obtained for the four municipalities) were as follows. First, the number of buildings located less than 100 m from the shoreline as well as the related built area, more than tripled between 1950 and 2011, increasing from 960 to 3158 units and from 17 to 58 ha, respectively (Duvat et al., 2016b). This mainly occurred in low-lying areas, due to coastal dune urbanisation, and in some places, to shoreline retreat that occurred along 30% of the 39.7 km-long studied coastline. This resulted *de facto* in the increase in the exposure of human assets, i.e. buildings and infrastructures (especially coastal roads), to both coastal erosion and marine inundation (Fig. 1). Assets' exposure, obtained by combining their distance to the shoreline and elevation (Fig. 1, Panel B), increased significantly over the period of analysis. In fact, the total built areas being in a critical (< 30 m from the shoreline and < 6 m high) and very critical (< 30 m from the shoreline and < 3 m high) situation were respectively multiplied by 3 and 9 over the last six decades.

Second, the terrestrial natural buffer zone composed of beach-dune systems experienced both a 70% decrease in area between 1950 to 2011 (from 673 to 208 ha) and a degradation of its buffering function due notably to the clearing of the indigenous vegetation by coastal residents (Fig. 2) (Duvat and Salmon, 2015). Local owners and the public

Panel A



Panel B

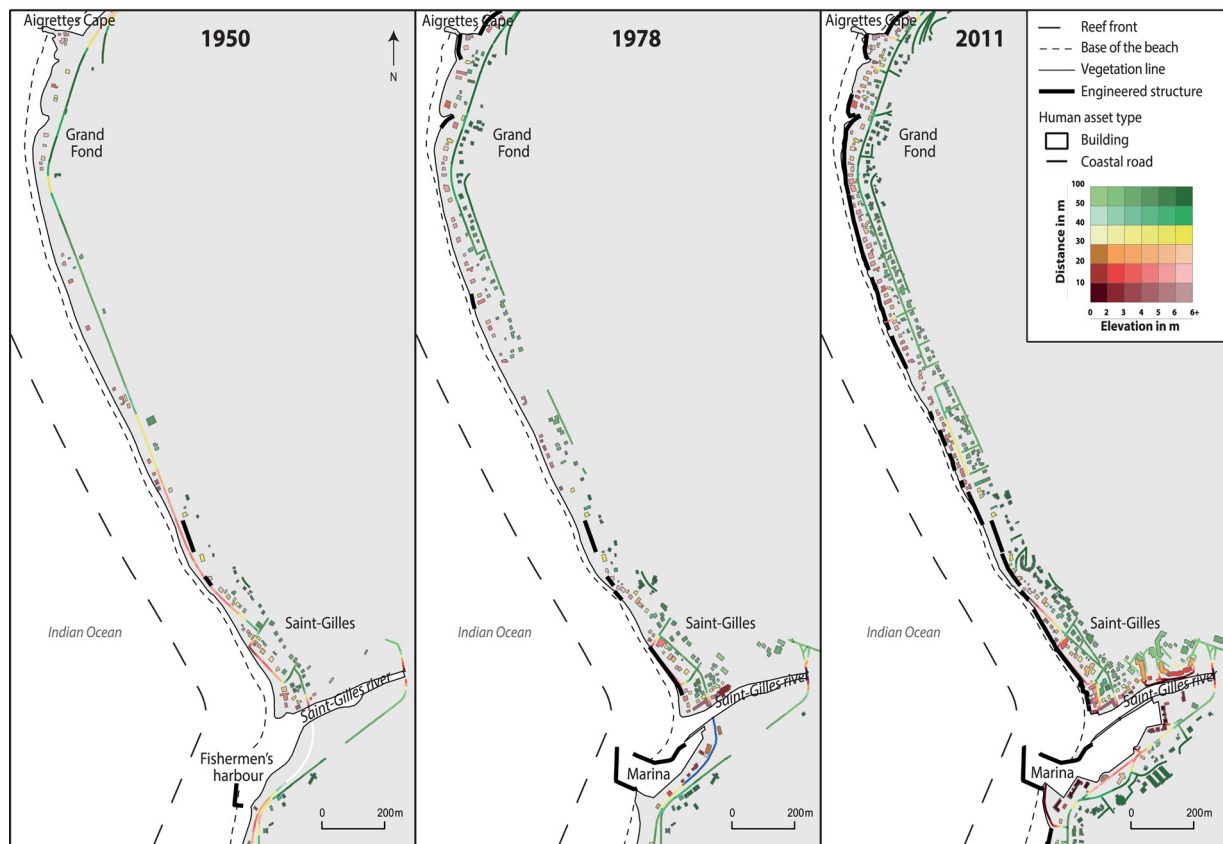


Fig. 1. Trends in human assets exposure to climate-related coastal hazards from 1950 to 2011.

Exposure was calculated by combining each asset's distance to the shoreline and elevation. The distance to the shoreline was calculated using either the vegetation line, or the base of engineered structures as a shoreline proxy, and is illustrated here for the 100 m-wide coastal strip considered as the “main threat zone” that should be free from construction under the French Littoral Law. **Panel A** illustrates the rapid extension and densification of the coastal built areas and road network in the four studied municipalities. **Panel B** shows a representative example (Grand Fond/Saint-Gilles area, in Saint-Paul municipality) of the past-to-present processes that have resulted in a rapid increase in vulnerability. It especially highlights the establishment of major developments in flood-prone areas (here, a marina located at a river mouth).

Source: adapted from Duvat et al. (2016b).

authorities progressively compensated the contraction of the natural buffer zone by fixing the shoreline with engineered structures, such as seawalls and rip-raps. As a result, 44% of the studied low-lying coastline are now equipped with hard structures, compared to 6% in 1950 and 13% in 1978. In addition, two-thirds of the 216 hard structures that we surveyed in 2013 are vertical cemented seawalls of less than 2 m high (mean of 1.07 m), which were built by coastal residents to protect

their property against trespassing or coastal hazards (Duvat and Salmon, 2015). Only one-third of the equipped coastline has proper engineering structures, built and maintained by the public authorities in order to protect highly exposed public infrastructures (e.g. Le Port's harbour facilities and Saint-Paul's coastal road) from wave attack or coastline retreat.

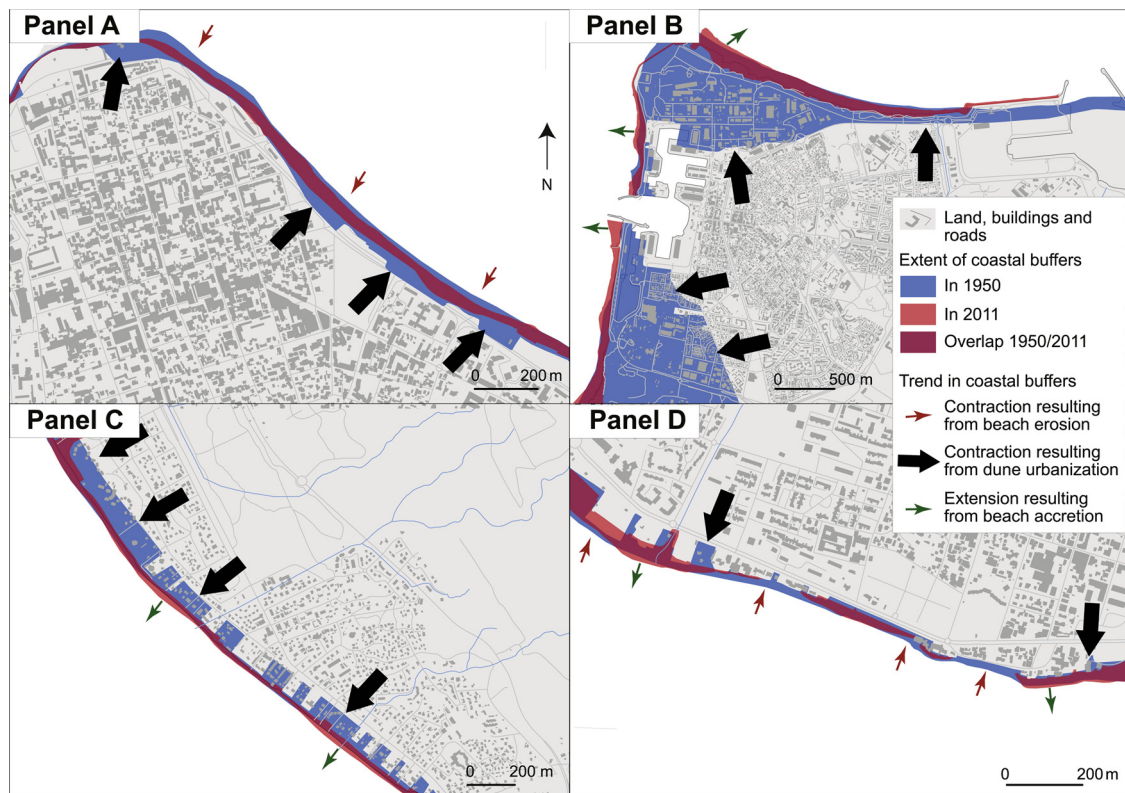


Fig. 2. Changes in the extent of coastal buffers from 1950 to 2011.

This figure describes the situation of the four studied municipalities, i.e. from North to South: the north-eastern coast of Saint-Denis (**panel A**); Le Port (**B**); the Salineles-Bains area in Saint-Paul municipality (**C**); and the coastal part of the city centre of Saint-Pierre (**D**). It emphasizes the widespread contraction of the terrestrial natural buffer zone as a result of coastal urbanisation (**panels A, C and D**) and economic development (**panel B**, i.e. harbour activities), and, in places, of the additional impact of coastline retreat (red arrows). On some coastal sections (e.g., Saint-Pierre, **panel D**) the marked contraction of the buffer zone has led to its disappearance, which considerably increased the exposure of human assets. This phenomenon, known as “coastal squeeze” (Cooper and McKenna, 2008; Cooper and Pile, 2014), constitutes one of the major root causes of settled areas’ vulnerability to current and future climate-related coastal hazards.

Source: adapted from Duvat and Salmon (2015) and Duvat et al. (2016b).

5. Implications for coastal adaptation

5.1. Policy implications

The above past-to-present coastal ToV highlights the prevailing environmental and anthropogenic drivers that operated over the last fifty to sixty years in Reunion Island, and that have the potential to continue driving vulnerability in the coming decades. This case emphasizes the imperative of stopping and then reversing wherever it is still possible, the urbanisation process, in order to reduce the anthropogenic pressures exerted on morphological-ecological systems and that are at the roots of the current coastal ToV. Furthermore, it highlights the imperative of restoring morphological-ecological systems’ buffering function and thereby natural adaptive capacity, as these latter have proved to be efficient in reducing cyclonic waves impacts where they are still functional (Duvat et al., 2016a). Such a major shift in public policies (i.e. urbanisation control associated with natural buffers restoration) also indirectly supposes to revise the current coastal defence strategy. That is, to move towards a less hard structure-dependant approach, as the amplification of such a strategy would inevitably generate exponential costs for maintenance and upgrading (Hinkel et al., 2014). Although looking trivial, such conclusions must actually be fully recognized as imperatives of coastal adaptation. A key reason is that climate change will mainly exacerbate context-specific, enrooted anthropogenic drivers of vulnerability (Cardona et al., 2012; Nurse et al., 2014; Wong et al., 2014), i.e. in the Reunion Island example, the detrimental effects of human disturbances on both the current response and the future adaptive capacity of coastal morphological-ecological

systems to climate-related pressures. Sea-level rise and the possible intensification of the most intense tropical cyclones (Bastone and De la Torre, 2011) will add a new layer of pressures on coastal buffers, and unless the anthropogenic drivers are challenged, this will translate into an increase in the exposure and vulnerability of human assets.

Addressing the above unavoidable strategies however supposes, besides consideration on economics and finance (Hinkel et al., 2018), both national to local stakeholders to be ready to drive that change. Recent interviews with almost thirty stakeholders (i.e. national and local authorities, business owners – see Section 3) revealed some converging views about both the way they envisage the near (~2025) and long-term (~2050) future of the island’s coastal areas, and how to address the related challenges (Magnan and Charpentier, 2016). Generally, they think that the future ToV will inevitably follow the last decades’ path, i.e. that coastal erosion will increase exponentially, thereby exacerbating human assets exposure, while terrestrial natural buffer zones would keep contracting. As a result, and almost unanimously advocating for “holding the line” (i.e. keeping the positions at the coast), they are favourable to the strengthening of the current hard defence-based strategy. Although they recognize that protecting natural buffer zones could be of value, they eventually mainly call for both the extension of engineered structures along the coastline and the upgrading of the existing structures. This position however raises serious doubts especially on the ability of the future society to hold the costs induced by such a one-way strategy. Besides questions about the long-term efficiency of the strategy *per se*, there is always a risk that the enabling conditions for such an efficiency will decrease over time, especially in terms of affordability. On this point, it is important to

remind that a key explaining factor of the 2005 hurricane Katrina catastrophe in New Orleans, United States, precisely relies in gaps in coastal protection maintenance due to a progressive decrease in both risk awareness and dedicated funds (Burby, 2006; Kates et al., 2006). The same happened prior to storm Xynthia in France in 2010 (Chadenas et al., 2013; Genovese and Przulski, 2013). Here we touch upon the root causes of vulnerability (Blaikie et al., 2004), and we argue that local stakeholders' current visions of the future set the floor of the future root causes of vulnerability. An encouraging sign is however that depending on the questions, one stakeholder out of five conceded the resort to coastal retreat will be necessary, although limiting this view to marginal areas where it is *a priori* thought that there will be few social reluctances and a consensus will be relatively easy to reach. But finally, despite such an emerging alternative vision, the business-as-usual view still dominates.

5.2. Societal acceptance of change

Implementing the above strategies also calls for local populations to be ready to support potentially constraining policies that will have benefits only in the future (Jones and Clark, 2014; Jones et al., 2015). On this point, complementary analyses on the Reunion Island case bring food for thought. The survey conducted among ~500 coastal residents on their perceptions of climate-related coastal risk (see Section 3) showed that while interviewees demonstrated an excellent appropriation of safety instructions, especially in case of a cyclone, more than 80% were unaware about official documents dealing with risk prevention and crisis management (Magnan et al., 2015). Two major ones are the *Plan Communal de Sauvegarde* that inventories the actions to be undertaken in case of a crisis, and the *Plan de Prévention des Risques* that regulates land use, including rules on building location allowance and building standards. This highlights a relative disconnection between coastal residents and the public authorities, what indirectly challenges the capacity of these latter to concretely implement new regulations on coastal urbanisation. The interviewees also under-estimated the role of anthropogenic drivers in coastal erosion, i.e. the adverse side effects of engineered structures on natural dynamics and shoreline change, what carries the risk of misunderstanding regarding possible new norms on coastal structures. This is all the more problematic that more than 50% of the interviewees considered climate change-related threats, especially sea-level rise and tropical cyclones intensification, to be a concern only for the long-term (~2050), but not for the near future (~2025). That is, they do not link current impacting anthropogenic activities and risk-related public decisions to the challenge of anticipating climate change impacts, which questions people's potential for acceptance of radical changes in collective action (Hornsey et al., 2016; Hino et al., 2017).

Together, these results suggest that in Reunion Island, the implications of climate change have not been yet tightly integrated to neither stakeholders' nor population's views about the future. However, as long as the cumulative risks induced by climate change are not fully recognized by all the components of the society, the business-as-usual unidirectional approach that explains past-to-present ToVs, will dominate coastal governance, henceforth seriously hampering efforts towards transformative adaptation. This is all the more disturbing that transformative adaptation is strongly about challenging societal inertia that is enrooted in institutional and/or societal processes (Bisaro and Hinkel, 2016). While the ToV approach clearly highlights some unavoidable solutions for coastal adaptation that have the potential to strongly limit the risk of maladaptation, barriers to adaptation rely on stakeholders' and residents' understanding of the way and of the need, respectively, to anticipate climate change impacts (Eisenack et al., 2014). This suggests that the problem with enhancing coastal adaptation pathways from now on is less about identifying the relevant solutions than about implementing already known ones, paving the way for the "unavoidable solutions" approach.

6. Discussion and conclusion: empirically-based and theoretical perspectives on the unavoidable solutions for coastal adaptation

Several lessons can be learnt from the Reunion Island case, as it provides empirically-based knowledge on how to enhance adaptation that also applies to a wide range of coastal situations worldwide (section 6.1). This in turn offers an opportunity to advance theoretical understanding of the leeway for adaptation further, especially by introducing the "unavoidable solutions" approach (6.2).

6.1. Practical insights

The study emphasizes four critical ways to enhance long-term adaptation from now on and thus reduce territories' exposure and vulnerability to climate-related coastal hazards over the next decades. Due to path-dependency effects inherent to past-to-present trends in coastal development (i.e., ToV), these critical ways form unavoidable solutions to reduce long-term vulnerability and, henceforth, constitute the basic bricks of any adaptation pathway (Barnett et al., 2014; Magnan et al., 2016), whatever the future warming scenario.

First, limiting the pressure exerted by urbanisation on natural buffers cannot still be overlooked if one really wants to slow down the process that controls coastal vulnerability (Cooper and Pile, 2014). In the foreseeable future, this will inevitably raise the challenge of re-locating people, assets and activities, inland or to higher coastal areas, making this solution full part of a necessary multiple responses strategy (Brown et al., 2014; Hino et al., 2017).

Second, there is a crucial need to allow natural morphological-ecological systems to recover their original buffering functions. This supposes to dramatically scale up the deployment of policies aiming at protecting the wealthiest systems and restoring the ones that have been degraded (Martin and Watson, 2016).

Third, driving these changes strongly supposes to move the public and private, and institutional and economic stakeholders' understanding about the future, away from the business-as-usual approach that consists in systematically keeping the positions at the coast. This latter unidirectional view is clearly incompatible with the adaptation challenge, especially under current accelerated sea-level rise. Cross-sectoral and cross-scale training is needed to raise stakeholders' awareness and knowledge on both social systems' path dependencies and climate change irreversible impacts, and henceforth on the need to enhance transformative policies in order to anticipate future risks. Here, practical methods such as role-play simulations can strongly help accelerating individuals' appropriation of multi-dimensional climate change implications (Rumore et al., 2014; Bécu et al., 2017).

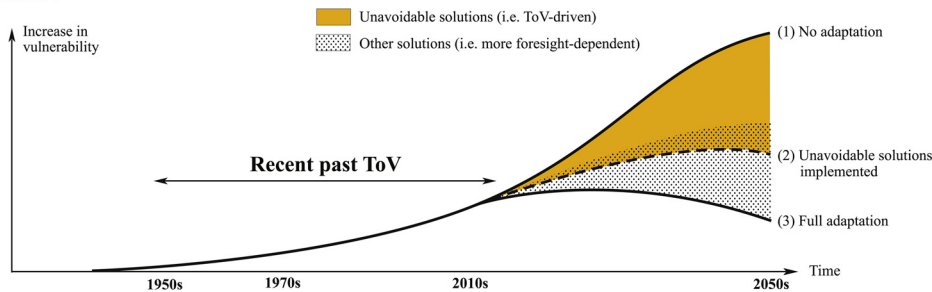
Last, the same applies to local populations if one expects them to accept and support new anticipatory policies such as coastal retreat, for example (Jones and Clark, 2014). It is indeed critical that coastal residents well understand the rationale behind such policies, as these latter will probably first impose constraints to residential, leisure and economic habits, to the advantage of (uncertain) future well-being.

6.2. Theoretical advances

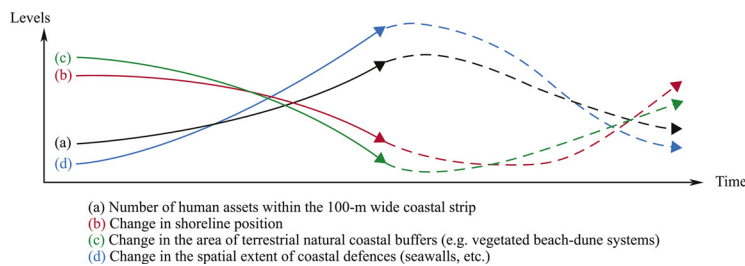
Such lessons learnt lay foundations for moving theoretical thinking further, especially through the concept of the "unavoidable solutions" for coastal adaptation. Building on the Reunion Island case, Fig. 3 describes a qualitative model (Panel A) of the changes that occurred in coastal areas' vulnerability from the 1950s to the mid-21st century (~2050). The changes (black thick curves, solid and dotted, in panel A) are represented for two different timespans. The observed trend from 1950 to today refers to the ToV summarized in Section 4. Hypothetical trends by ~2050 describe the future changes in the ToV according to various level of implementation of adaptation measures. The right-hand side of Panel A presents three generic situations.

Curve (1) illustrates a business-as-usual scenario composed of the

Panel A



Panel B



continuation of the past-to-present ToV resulting in a significant increase in vulnerability. It shows the situation where no adaptation is implemented, or at best some sporadic incremental options such as the relocation of a few houses or the partial protection of an endangered coastal dune or beach.

Curve (2) represents an adaptation pathway that fully considers the lessons learnt from the past-to-present ToV analysis, and hence where the full range of unavoidable solutions (orange area) is implemented. It shows that in theory, a significant reduction in vulnerability can be expected from such a scenario. Panel B in Fig. 3 illustrates this scenario for the Reunion Island case by showing the contribution of the above-analysed four main drivers to the observed ToV (coloured solid curves on the left-hand side) and a possible future adaptation pathway (coloured dotted curves on the right-hand side). It notably shows an inversion by ~2050 of the observed trends for all drivers:

- The reduction in the number of human assets located within a 100 m-wide coastal strip ((a), black lines);
- Shoreline natural readjustment, i.e. return to stability ((b), red lines) as a result of decreasing anthropogenic disturbances, artificial beach/dune nourishment, vegetation planting and the maintenance of cyclone-driven sediment deposits;
- The recovery of natural buffers ((c), green lines), e.g. restoration of a 100 m-wide unbuilt coastal strip and allowing the recovery of coastal systems' buffering function through both ambitious policy and public awareness raising;
- A marked decrease in the length of coastline equipped with engineered coastal defences ((d), blue lines), except in already densely urbanised erosion- and flood-prone areas.

Last, curve (3) in Panel A represents the ideal adaptation scenario where other solutions complement the full implementation of the ToV-driven unavoidable solutions, then leading to the minimization, not to say the eradication in the best-case scenario, of vulnerability. Such other solutions are represented in Fig. 3 by the stippling area and refer to measures that are not directly ToV-driven (e.g. construction of buildings and roads on stilts to allow for natural sediment movement and deposition). While the unavoidable solutions category essentially relies on “doing well what we currently do badly”, the other solutions category is *a priori* more foresight-dependent, not necessarily from a technological point of view, but at least in terms of decision-making and policy processes. Fig. 3 suggests that in theory, there can be some

overlap between the orange and stippling surface areas. This indicates that depending on the context-specificities, the respective contribution from the ToV-driven unavoidable and the more foresight-dependent measures to full adaptation by ~2050 can vary from one case study to another.

Author contributions

AKM and VKED together designed the research, produced the results and wrote the manuscript.

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